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METHOD AND APPARATUS FOR CONTROLLING POWER FACTOR CORRECTION

BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

[01] The present invention relates to power factor corrections, and more specifically to multiple mode power factor correction.

DESCRIPTION OF THE RELATED ART

[02] An electrical load may appear to a power supply as a resistive impedance, a capacitive impedance, an inductive impedance, or a combination thereof. When the current is in phase with or at least very close to being in phase with the voltage, the power factor is said to be good. When an electrical load is purely resistive, the current passing to the load is proportional to the voltage crossing the load. The power factor of such an electrical load is to one. The power factor is less than one in all other situations. If an electrical load is not purely resistive, it introduces noise into the power line. To reduce the noise to the power line caused by electrical loads, nowadays, power supplies with an electrical power output above 30 watts are required to have power factor corrections, so as to shape the input current waveform to follow the input voltage waveform.

[03] Boost converters are used for power factor correction. Fig. 1 shows a block diagram of one example of a boost converter. A capacitor 101 filters input current ripple. A four-way rectifier 102 rectifies an input voltage V_{in}. When a boost switch 103 is closed, an operating cycle starts. The power source V_{in} charges a boost inductor 104 via an input current I_{in}, and energy is stored in the boost inductor 104. When I_{in} reaches a value determined by a

controller 105, the controller 105 outputs a signal to open the boost switch 103, and the inductor 104 discharges via a load 106. When the boost switch 103 has been opened for a period of time determined by the controller 105, or the input current I_{in} falls to a value determined by the controller 105, the controller 105 outputs a signal to close the boost switch 103, and the next operation cycle starts. A boost diode 107 prevents current from flowing back to the boost inductor 104 from the load 106. A capacitor 108 filters high frequency noises of the rectified V_{in} and a capacitor 109 removes ripples in the output voltage V_{out}.

[04] Conventional boost converters use one of three operation modes: continuous mode (also called average current mode), discontinuous mode, or critical mode, but can not switch among them.

[05] Fig. 2A shows a block diagram of a conventional power factor correction controller for the continuous mode. A power factor correction controller has two tasks. The first is to regulate the output voltage V_{out} to keep it stable. The second is to regulate the input current I_{in} to make it follow the waveform of the input voltage V_{in}, mimicking that the load is purely resistive. As shown, a subtractor 201 subtracts a reference voltage V_{ref} from the output voltage V_{out} to obtain a voltage error V_{err}, which is then amplified by a voltage amplifier 202. The subtractor 201 and the voltage amplifier 202 are used to regulate V_{out} to keep the output stable.

[06] The input voltage is a sine wave. To make a load appear as a purely resistive load, the input current needs to be regulated as a sine wave in the same phase as the input voltage. A multiplier 203 multiplies the amplified V_{err} from the voltage amplifier 202; the rectified input voltage V_{inrec}; and the normalized root mean square value of the rectified input voltage V_{inrec} from a low pass filter 204 and a normalizer 205. The output of the multiplier 203 is a factor

C_{ref}. A subtractor 206 subtracts the factor C_{ref} from the input current I_{in} of the boost converter, obtaining a current error C_{err}, which is amplified by an amplifier 207 and is then used to control a pulse width modulator (PWM) 208.

[07] The period, T_s, of the charging and discharging cycle in the continuous mode is fixed. The charging time is determined by the amplified current error C_{eaout}. Thus, the discharging time is T_s minus the charging time. The resulting switch voltage V_{sw} is then used to control the boost switch 103 shown in Fig. 1.

[08] Fig. 2B illustrates the voltage waveform and current waveform of a conventional boost converter in continuous mode. The current in continuous mode never goes to zero, except at the edges. The benefit of running continuous mode is lower ripple current, so that the controller only needs a small input filter. However, at a given power level, if the continuous mode is used, the size of the inductor must be large in the full cycle.

[09] Fig. 3A shows a block diagram of a conventional power factor correction controller for the critical mode. Similarly to the power factor correction controller shown in Fig. 2A, the power factor correction controller for the critical mode obtains an amplified voltage error by a subtractor 301 and a voltage amplifier 302. A zero current detector 303 finds zero current points in the input current I_{in}. A PWM 308 is coupled to the outputs of the voltage amplifier 302 and the zero current detector 303. In the critical mode, the charging time is fixed and is determined by the voltage amplifier 302, and the boost inductor 104 keeps discharging until a zero current point is met.

[10] Fig. 3B illustrates the voltage waveform and current waveform of a conventional boost converter for the critical mode. As shown, the boost inductor keeps discharging until a

zero current point is met. When the critical mode is used, the size of the inductor can be small, but the ripple current is very high, thus requiring large input filter.

[11] Fig. 4 illustrates the voltage waveform and current waveform of a conventional boost converter in discontinuous mode. As shown, the input current I_{in} remains off for a certain time interval between each charging and discharging cycle. The discontinuous mode also has high ripple current and needs a large input filter.

[12] Another disadvantage of conventional boost converters is that their current harmonic distortions start to increase when the load is lowered.

[13] A further disadvantage of the conventional boost converters is that their responses in certain frequency bands are very slow. If they respond too fast, there will be large spikes.

[14] Therefore, it would be advantageous to provide a method and apparatus for controlling the boost converters in multiple modes during power factor correction, so as to keep both the boost inductor and the input filter small.

SUMMARY OF THE INVENTION

[15] In view of the foregoing, it is an object of the present invention to provide a power factor correction controller, which dynamically changes operation mode of a boost converter during a half cycle of the voltage, thus gaining the benefit of small size inductor, low harmonic distortion, and small ripple current. A digital signal processor calculates the duty cycle and frequency of the boost switch. In one embodiment, when the phase of the voltage is roughly between 45 degrees and 135 degrees, the voltage is high, and the controller forces the boost converter to operate in continuous mode by adjusting the frequency and duty cycle

of the boost switch. Beyond this range, the controller forces the boost converter to operate in critical or discontinuous mode.

[16] It is another object of the present invention to provide a controller for power factor correction for a variable load. The controller senses the input current continuously and switches the operation mode automatically according to the load to improve the response. The operation is in continuous mode when the load is high, and in the critical mode when the load is reduced.

[17] It is another object of the present invention to provide a controller for power factor correction, which switches operation mode from average current mode to critical mode when a zero current is detected before the charging and discharging cycle is finished.

BRIEF DESCRIPTION OF THE DRAWINGS

[18] The present invention is described herein with reference to the accompanying drawings, similar reference numbers being used to indicate functionally similar elements.

[19] Fig. 1 shows a block diagram of one example of a boost converter.

[20] Fig. 2A shows a block diagram of a conventional power factor correction controller for continuous mode.

[21] Fig. 2B illustrates the voltage waveform and current waveform of a conventional boost converter in continuous mode.

[22] Fig. 3A shows a block diagram of a conventional power factor correction controller for critical mode.

[23] Fig. 3B illustrates the voltage waveform and current waveform of a conventional boost converter in critical mode.

[24] Fig. 4 illustrates the voltage waveform and current waveform of a conventional boost converter for discontinuous mode.

[25] Fig. 5A shows a block diagram of an apparatus for power factor correction, employing a multiple mode controller according to one embodiment of the present invention.

[26] Fig. 5B illustrates the voltage waveform and current waveform of a multiple mode boost converter according to one embodiment of the present invention.

[27] Figs. 6A-D illustrate plots of variables of a boost converter employing a controller according to one embodiment of the present invention.

[28] Figs. 7A-D illustrate plots of variables of a boost converter employing a conventional controller.

[29] Fig. 8A shows a block diagram of a power factor correction controller for multiple mode operation according to another embodiment of the present invention.

[30] Fig. 8B illustrates the voltage waveform and current waveform of a boost converter employing the multiple mode controller shown in Fig. 8A.

[31] Fig. 9 shows a block diagram of a single-tone notch filter according to one embodiment of the present invention.

DETAILED DESCRIPTION OF EMBODIMENTS

[32] Objects and advantages of the present invention will become apparent from the following detailed description.

[33] Fig. 5A shows a block diagram of an apparatus for power factor correction, employing a multiple mode controller according to one embodiment of the present invention. The controller 505 shown in Fig. 5A can dynamically switch the operation mode of the boost

converter among continuous mode, critical mode, and discontinuous mode. The controller 505 is a DSP (Digital Signal Processor). In one embodiment, the controller 505 is an ASIC (Application Specific Integrated Circuit). Other embodiments for controller 505, including microprocessors and other hardware/software/firmware implementation will be apparent to ordinarily skilled artisans. Other parts of the boost converter shown in Fig. 5A are similar to those shown in Fig. 1.

[34] As shown, the controller 505 obtains inputs at points X, Y, and Z. The controller 505 senses a zero crossing voltage at point X; senses a voltage at point Y to maintain the output voltage stable; and senses the current at point Z to predict the load behavior.

[35] The sensed voltage signals at point X are converted to digital signals by an A/D converter 510. A zero crossing voltage locator 511 finds out zero crossing voltages, and output them to a predictor 512 and a peak detector 520. The predictor 512 determines the frequency of the input voltage and the locations of the point with 90 degree phase. A peak detector 520 obtains the voltage magnitude of this point, the peak voltage, and sends the peak voltage to the predictor 512.

[36] In one embodiment, the predictor 512 has a predictive look up table. One form of the predictive look up table, in which D represents duty cycle, is as follows.

Frequency	Vin	Equations
50Hz	220V	$D = 1 - \frac{220\sin\theta}{V_{out}}$
50Hz	230V	$D = 1 - \frac{230\sin\theta}{V_{out}}$

50Hz	240V	$D = 1 - \dfrac{240\sin\theta}{V_{out}}$
60Hz	120V	$D = 1 - \dfrac{120\sin\theta}{V_{out}}$
60Hz	277V	$D = 1 - \dfrac{277\sin\theta}{V_{out}}$

[37] Thus, instead of continuously following and sampling the input voltage signal, as the conventional power factor correction controller does, the controller 505 only detects the zero crossing points and the peak voltage magnitude. The predictor 512 predicts the waveform of the input voltage according to the zero crossing points, the peak voltage, and the characteristics of the sine wave. The predictor 512 then outputs to the DSP 513 a set of equations corresponding to the waveform of the input voltage signal.

[38] The DSP 513 also receives a voltage signal from point Y via an A/D converter 517 and a notch filter 516. The notch filter 516 removes harmonic ripples of the input voltage feeding into the loop. In this embodiment, the frequency of the input voltage is 60 Hz, and the notch filter 516 removes a narrow band of frequencies around 120 Hz, or twice the frequency of the input signal.

[39] The DSP 516 further receives a current signal from point Z via an A/D converter 519 and a filter 518. The DSP 513 then calculates the duty and frequency of the boost switch according to the equations from the predictor 512, the voltage signal from point Y, and the current signal from point Z.

[40] The main relations in the boost converters are as follows:

[41] I_A=i_ideal/(D1+D2)+v_rail *D1*Tsw/(2*L_b);

I_B=i_ideal/(D1+D2)-v_rail *D1*Tsw/(2*L_b); and

V_{out}/v_rail=(D1+D2)/D2, (1)

[42] wherein I_A refers to the maximum charging current;

I_B refers to the minimum discharging current;

i_ideal refers to the current making the load 506 appear as a purely resistive load, and can be calculated from the input voltage predicted by the predictor 512 and the impedance of the load 506;

D1 refers to the turn on time of the boost switch 503;

D2 refers to the turn on time of the boost diode 507;

v_rail refers to the rectified V_{in}, or the voltage at point X;

T_{sw} refers to the period of the boost switch 503; and

L_b refers to impedance of the boost inductor 504.

[43] For continuous mode, D1+D2=1. Thus, I_A, I_B, D1 and D2 can be calculated from equation (1).

[44] For discontinuous mode, I_B=0, and D_{gap} =1-D1-D2. Thus, I_A, D1 and D2 can be obtained from equation (1).

[45] In one embodiment, the DSP 513 uses the following coefficient matrix to calculate a duty cycle of the boost switch 503:

A=[L_b, -L_b, -v_rail(i) *T_{sw}(k); L_b, -L_b, (v_o(i) –v_rail(i))*T_{sw}(k); 1, 1, 0];

$B=[0; (v_o(i) - v\_rail\ (i))*T_{sw}(k); 2*i\_ideal(i)];$

$X=A\backslash B,$ (2)

wherein,

$v\_rail(i) = 2+abs(V_m*sin(wt(i)));$

$V_m=sqrt(2)*V_{in\_low};$

$wt\ (i) = i*Del\ (k);$

$Del(k)=20*pi/Fsw(k);$

$Fsw(k)=1/Tsw(k);$

$Tsw(k) = [4*L_b/(effcy*V_m\hat{}2*D1\_pk)*(P_{o\_rated}-P_{out}(k))+1/Fsw\_mx];$

$v_o(i) = V_{out} + (v_{o\_ripp}/2)*sin(2*wt(i));$

$i\_ideal\ (i) = 0.1 + abs(I_m(k)*sin(wt(i)));$

$P_{out}(k)=kk*P_o\_rated;$

$k=1:10$

$kk=(11-k)/10.$

[46] If x(2)>0, then

$I_A(i) = x(1);$

$I_B(i) = x(2);$

$D1(i) = x(3);$ and

$D2(i)=1-D1(i).$

By solving the coefficient matrix (2), I_A, I_B, D1 and D2 can be obtained. If 0.2<D1(i)<1, D2(i) = 1-D1(i). In this situation, the load is large, and the boost converter operates in continuous mode.

[47] If 0<D1(i) ≤0.2, then

I_B(i) =0;

I_A(i) =2*i_ideal (i);

D1(i) =L_b*(I_A(i)-I_B(i))*F_{sw}(k)/v_rail(i); and

D2(i)=1-D1(i).

[48] In this situation, the boost converter operates in critical mode.

[49] If x(2) ≤0, and (pi/6>wt(i) | wt(i) >5*pi/6), or x(2)) ≤0, and (pi/6<wt(i)<5*pi/6), then

I_B(i)=0;

D1(i)=0.5,

D2(i)=L_b*(I_A(i)-I_B(i))*F_{sw}(k)/v_o(i)-v_rail(i)); and

D_{gap} (i) =1-D1(i)-D2(i)

[50] In this situation, the boost converter operates in discontinuous mode.

[51] The DSP 513 calculates the charging current, the discharging current, the boost switch turn on time, and the boost diode turn on time according to the rectified input voltage, the output voltage, and the load behavior, and adjusts the duty cycle and frequency of the gate voltage V_{sw} of the boost switch 503 accordingly. The DSP 513 then sends the gate voltage

via an D/A converter 514 and a driver 515. Consequently, the waveform of the input current is made to follow the waveform of the input voltage, even when the load is variable.

[52] Fig. 5B illustrates the voltage waveform and current waveform of a multiple mode boost converter according to one embodiment of the present invention. As shown, the boost converter operates in continuous mode at the peak of the input voltage, in discontinuous mode at the beginning and end of the half input voltage cycle, and in critical mode during the transition of these two modes.

[53] Figs. 6A-D illustrate plots of variables of the multiple mode boost converter according to one embodiment of the present invention. Figs. 6A-C indicate the change of rectified rail voltage, duty cycle, and upper and lower current of switch with respect to line angle in radian, and Fig. 6D indicates the change of switching frequency with respect to output power.

[54] Figs. 7A-D illustrate plots of variables of a conventional converter. Similarly, Figs. 7A-C indicate the change of rectified rail voltage, duty cycle, and upper and lower current of switch with respect to line angle in radian, and Fig. 7D indicates the change of switching frequency with respect to output power.

[55] Fig. 8A shows a block diagram of a multiple mode power factor correction controller according to another embodiment of the present invention. A controller 800 adjusts the operation mode of a boost converter according to the loading. When the loading is high, the controller 800 controls the boost converter to operate in the continuous mode. When the loading is low, the controller 800 changes the operation mode of the boost converter to the critical mode.

[56] The controller 800 comprises most of the blocks of the controller 200 shown in Fig. 2A, including a subtractor 801, a multiplier 803, a subtractor 806, and a current amplifier 807. Similar reference numbers are used to indicate functionally similar blocks.

[57] As shown, two A/D converters 809 and 816 convert analog signals for digital domain processing. A rectifier 805 rectifies the input voltage V_{in}. A zero crossing detector 814 determines the zero crossing points in the rectified input voltage V_{inrec}. A period estimator and phase generator 815 determines the period of the rectified input voltage V_{inrec} and the phase θ of an instant point of V_{inrec}. A sine wave of θ is created and provided to the multiplier 803.

[58] A sine wave and a cosine wave of integral times of θ are created and provided to a digital notch filter 810 so as to remove harmonic ripples in the output voltage V_{out}. In this embodiment, a sine wave and a cosine wave of 2θ are provided to the notch filter 810. A voltage range estimator 813 provides the voltage range of the rectified input voltage V_{inrec} to a gain selector 812.A detector 811 detects over-voltage and under-voltage in the voltage error V_{err} and provides such information to the gain selector 812. The gain selector 812 then determines the gain of a loop filter 802, which is also a voltage amplifier, to provide over-voltage protection.

[59] The voltage error V_{err} from the subtractor 801 is sampled by the A/D converter 809, filtered by the notch filter 810, and amplified by the loop filter 802 according to the gain from the gain selector 812. The phase θ, its sine wave, and the amplified V_{err} (V_{eaout}) are multiplied to generate a factor C_{ref}. A subtractor 806 subtracts the factor C_{ref} from the sampled input current I_{in}, obtaining a current error C_{err}. The current amplifier 807 provides C_{eaout}, amplified current error C_{err}, to a PWM controller 808. The PWM controller 808 then

generates a voltage pulse to control the switch 103 shown in Fig. 1 according to signals from the current amplifier 807, a zero current detector 817 and an over current detector 818. When the current exceeds the over current limit, the over current detector 818 opens the switch.

[60] The multiple mode controller shown in Fig. 8A combines the average current mode and the critical mode. The charge time of the multiple mode controller is the same as that of the average current mode. The normal period for charging and discharging the boost inductor 104 in mixed mode, T_s, is also the same as that of the average current mode. The controller 800 adjusts the operating mode by controlling the start of the recharging. When a zero current is detected before T_s expires, the controller 800 changes the operating mode to critical mode by closing the boost switch 103 to start recharging of the boost inductor. Otherwise, the boost converter continues to operate in the average current mode by starting recharging of the boost inductor after T_s expires.

[61] Fig. 8B illustrates the voltage waveform and current waveform of a boost converter employing the multiple mode controller shown in Fig. 8A. As shown, when the phase of the input voltage is close to 0° or 180°, the loading is relatively low, the boost converter operates in critical mode. When the phase of the input voltage is close to 90°, the loading is relatively high, the boost converter operates in average current mode.

[62] The notch filter 810 could be single tone or multi-tone. Fig. 9 shows a block diagram of a single-tone notch filter according to one embodiment of the present invention, wherein ϕ is the phase of the second harmonic of the rectified input voltage V_{inrec}, and μ represents bandwidth selection or step size of the adapter. The notch filter removes the harmonic ripples by operations to the sine wave and cosine wave of the phase of the harmonic. When the

frequency of the input is 60Hz, the digital notch filter can be configured to remove harmonic ripples of 120 Hz, 180 Hz and so on.

[63] The method and apparatus of the present invention can be used in any power supply. While the invention has been described in detail above with reference to some embodiments, variations within the scope and spirit of the invention will be apparent to those of ordinary skill in the art. Thus, the invention should be considered as limited only by the scope of the appended claims.